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REFLECTION PROPERTIES OF SCARABAEIDAE

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Beetles of the scarab family have been found to reflect circularly polarized light from incident unpolarized light. There are many known animals that use polarized light in some form and several that actually create it, but there are few examples of the creation of circularly polarized light in nature. Previous work is summarized, and new measurements of several scarab specimens are presented.

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Reflection properties of Scarabaeidae

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ABSTRACT

Beetles of the scarab family have been found to reflect circularly polarized light from incident unpolarized light. There are many known animals that use polarized light in some form and several that actually create it, but there are few examples of the creation of circularly polarized light in nature. Previous work is summarized, and new measurements of several scarab specimens are presented.

1. INTRODUCTION

The creation of polarized light is common in nature, but the generation of circularly polarized light from unpolarized light is quite rare. A. A. Michelson noted in 1911[1] that reflected light from the scarab beetle *Plusiotis resplendens*, a beetle that appears to have been fashioned out of brass or gold, is circularly polarized. Later authors have discussed this effect as well[2-9] and it has been found that only scarabs possess the ability to generate circularly polarized light. Fig. 1a shows *Plusiotis resplendens* in the absence of polarizing optics, and Fig. 1b shows the animal with a circular polarizer in front of the camera. The effect for this creature is more subtle than other scarabs; it is difficult to discern the difference between these two images. A more impressive example is *Plusiotis gloriosa*, shown in Fig. 2. I have examined several of these scarabs for this study and have measured the spectral reflectance and Mueller matrix for the visible region in order to quantify this effect. In Section 2 I review the instrumentation used to make the spectropolarimetric measurements, and in Section 3 I discuss data reduction issues. Results are presented in Section 4, and conclusions are drawn in Section 5.

a. No polarizer b. Circular polarizer in front of camera
Figure 1: *Plusiotis resplendens*

a. No polarizer b. Circular polarizer in front of camera
Figure 2: *Plusiotis gloriosa*

2. DUAL ROTATING-RETARDER MUELLER MATRIX POLARIMETER AND MUELLER MATRIX REFLECTOMETER

An instrument that measures spectral polarization properties of materials in transmission and reflection has been previously designed, patented[10], and described[11]. The spectropolarimetric reflectometer is based around a commercial Fourier transform spectrometer. The spectropolarimeter generates radiation from the ultraviolet to the far infrared, and has a Visual Basic executive program that allows control over the spectrometer, control over motorized rotation stages, and spectropolarimetric data processing. The spectrometer is a Bio-Rad FTS-6000 with Win-IR Pro software. For purposes of the measurements described here, the spectrometer is used with one source, a xenon lamp, and one silicon detector. The Bio-Rad spectrometer serves as a radiation source for the polarimetric portion of the instrument and is operated in the conventional absorption spectroscopy mode. The radiation generated by the spectrometer is brought out through the spectrometer's external port. Fig. 3 shows the basic optical schematic of the instrument for monostatic reflectance measurements. The detector is fixed in the position shown. The sample is mounted a short distance past the beamsplitter. The optical system that collects light for the detector consists of an off-axis parabolic mirror. This mirror is fixed to look toward the beamsplitter and focus light onto the detector that is mounted perpendicularly to the light coming from the beamsplitter. The parabolic mirror, detector, and mounting devices are referred to as the detector assembly. The sample is mounted vertically. The reflectometer may be used without any modification of the polarization of the source radiation, i.e., no polarization elements, and in this mode, it is a spectral reflectometer. In order to obtain spectropolarimetric measurements, a dual rotating retarder Mueller matrix polarimeter, described by Azzam[12], is included in the system. This polarimeter consists of a polarization state generator before the sample and a polarization state analyzer after the sample. The polarization state generator consists of a linear polarizer followed by a quarter wave retarder. The polarization state analyzer consists of a quarter wave retarder followed by a linear polarizer in front of the detector assembly. Although I use retarders that are nominally quarter wave in the spectral region being measured, the exact retardance is not critical. When the retarders are rotated in a five to one ratio, all sixteen elements of the sample Mueller matrix are encoded onto twelve harmonics of the detected signal, which can then be Fourier analyzed to recover the Mueller matrix elements. Other previous implementations of this Mueller matrix polarimeter have been described elsewhere[13].

3. DATA REDUCTION AND ERROR COMPENSATION

The data reduction algorithm for this polarimeter as originally presented by Azzam assumes ideal polarization elements and no orientation errors. The data reduction algorithms may be generalized to compensate for systematic errors that result when orientation misalignment and non-ideal retarders are used. If the polarization elements are rotationally misaligned, or the retarders do not have exactly one-quarter wave of retardance, the changes in Fourier amplitudes and phases result in errors in the sample Mueller matrix. Even small orientation and retardance errors (<1°) can lead to large errors in the measured Mueller matrix (> 10% in some matrix elements). These errors become especially important when the retardance and alignment vary

significantly from their nominal values such as in multi-wavelength or spectral instruments. I have incorporated correction terms for orientation and retardance errors into the dual rotating retarder data reduction algorithm. These correction terms are collected during calibration of the instrument. Small angle approximation error correction equations are given in Goldstein and Chipman[14], and this is generalized to larger angles in Chenault et al.[15] These equations are quite lengthy and will not be presented here.
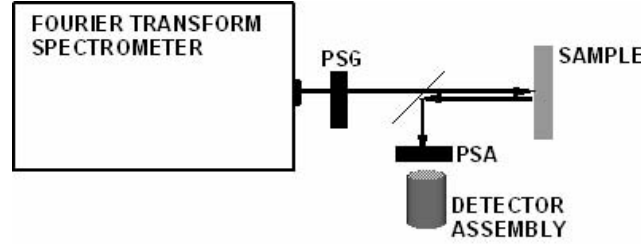

Figure 3: Monostatic spectropolarimetric reflectance measurement configuration

The beamsplitter indicated in Fig. 3 is a polka-dot beamsplitter, i.e. a plate to which silvered dots have been applied. This type of beamsplitter produces good achromatic performance. There is no off-the-shelf beamsplitter known to this author that does not introduce retardance. Beamsplitters that produce a 50/50 split with no retardance have been designed[16], but they have not yet been fabricated. Because of this residual retardance in the beamsplitter, the measured Mueller matrix will contain a retardance that is not associated with the sample. This must be removed to obtain the true Mueller matrix of the sample.

The apparent measured Mueller matrix of the sample is the product of three component Mueller matrices. In order of light transmission, these are 1) the Mueller matrix of the beamsplitter in transmission, 2) the Mueller matrix of the sample, and 3) the Mueller matrix of the beamsplitter in reflection on the beam reflection from the sample. The measured Mueller matrix can then be expressed as

$$M_{measured} = M_{BSR} M_S M_{BST}$$
(1)

where the subscript BSR indicates the beamsplitter in reflection and the subscript BST indicates the beamsplitter in transmission. The true Mueller matrix of the sample can be found by solving the equation for M_S so that

$$M_S = M_{BSR}^{-1} M_{measured} M_{BST}^{-1}.$$ (2)

M_{BST} can be measured directly by removing the sample and placing the polarization state analyzer and detector assembly in line with the original beam. M_{BSR} is found indirectly. The sample is replaced by a high-quality front surface aluminum mirror placed normally to the beam in the original instrument configuration as in Figure 3. The Mueller matrix for an ideal mirror is

$$M_M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}.$$ (3)

M_{BSR} is then

$$M_{BSR} = M_T M_{BST}^{-1} M_M^{-1}$$ (4)

where M_T is the measured Mueller matrix through the whole system with the mirror in the sample position. Measured retardances on the order of 15° have been found for commercial 50/50 beamsplitters designed to be nonpolarizing and used at 45°.

Having established the beamsplitter retardances, the polarimetric reflectometer is operated and saves the data that has been corrected for Mueller matrix polarimeter errors as described in Section 2. The data is then compensated for beamsplitter retardances in Mathcad or MATLAB programs that also plot the data. Tests have been performed with the mirror and other samples to insure that residual retardances all originate from the beamsplitter.

4. MEASUREMENT RESULTS

Results of measurements of the two scarabs in Figs. 1 and 2 are shown in Figs. 4-7. All data was collected at 16 cm^{-1} resolution. Fig. 4 shows the spectral reflectance of *Plusiotis gloriosa* while Fig. 6 shows the spectral reflectance for *Plusiotis resplendens*. The large spike in each of these plots at 0.6328 μm is due to the Helium-Neon laser in the spectrometer. From Fig. 4 it is evident that most of the reflected light from *Plusiotis gloriosa* is in the green to yellow with two peaks at about 0.53 μm and 0.58 μm. *Plusiotis resplendens* has a more uniform reflectance distribution with most of the energy at the yellow to red end of the spectrum.

The Mueller matrices for these two scarabs are shown in Figs. 5 and 7, and show objects that are unlike anything else I have measured. The Mueller matrix for *Plusiotis gloriosa* in Fig. 5 is almost a textbook example of a matrix for a homogeneous nonlinear (circular) polarizer, i.e.

$$\begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix}.$$
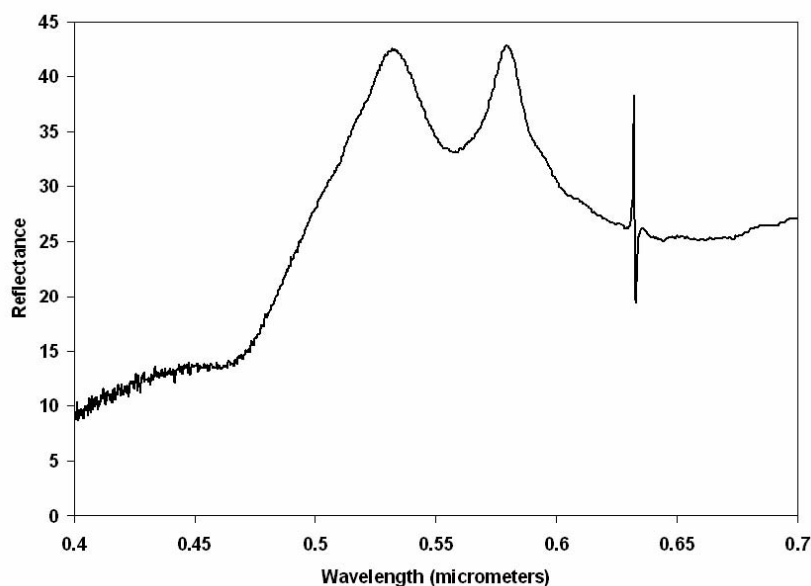

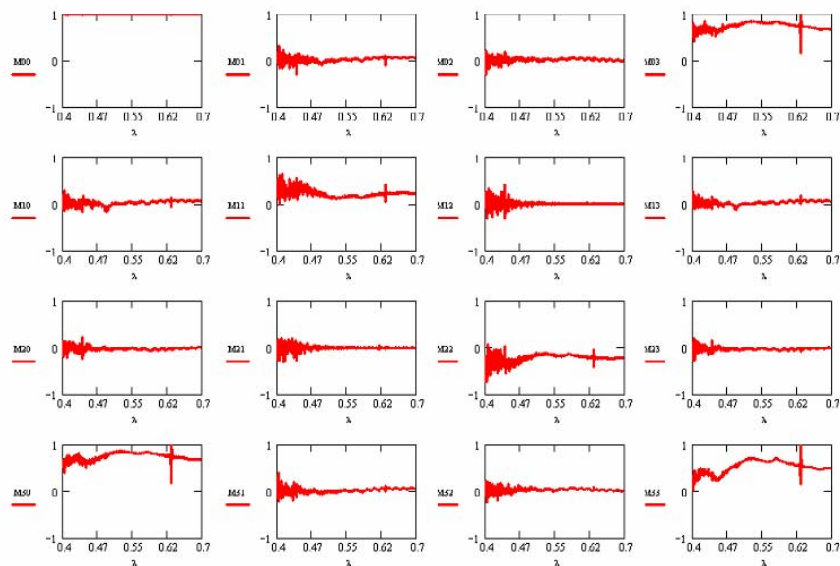Figure 4: Spectral reflectance of *Plusiotis gloriosa*

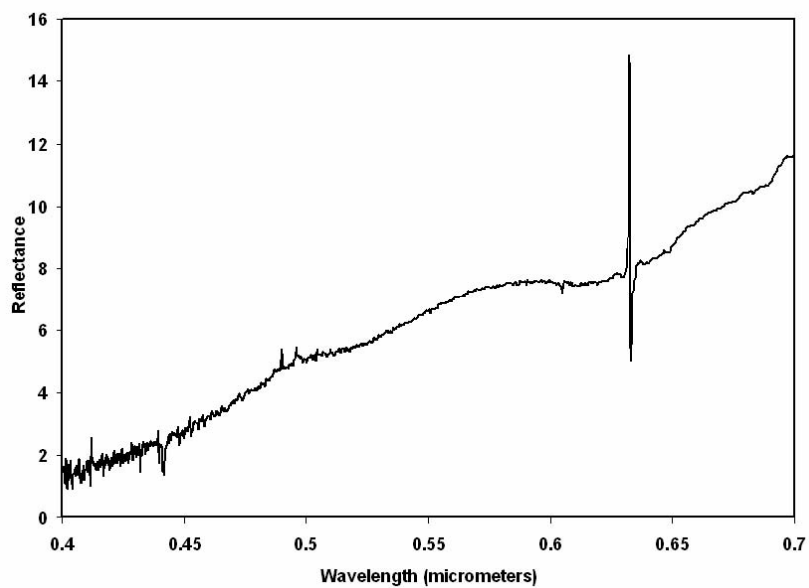Figure 5: Mueller matrix for *Plusiotis gloriosa*

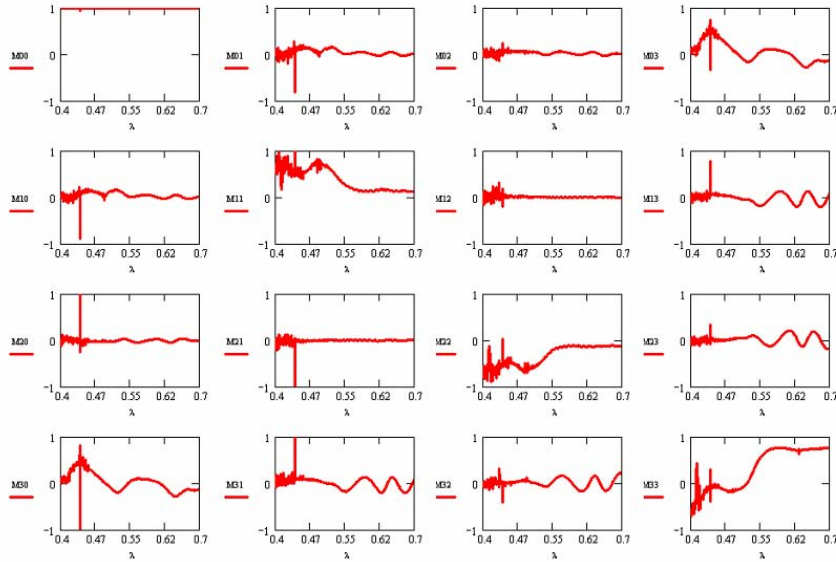Figure 6: Spectral reflectance of *Plusiotis resplendens*

Figure 7: Mueller matrix for *Plusiotis resplendens*

The behavior of the Mueller matrix for *Plusiotis resplendens* has more features. The matrix is of an object that generates circularly polarized light from unpolarized light but with considerable variation from one end of the visible spectrum to the other. At the same time, at the short wave end of the spectrum it has mirror-like qualities. The hand of the matrix component generating circularly polarized light from unpolarized light, M30 in Fig. 7, actually reverses twice in going from 0.4 to 0.7 μm.

5. CONCLUSIONS

I have presented reflectance spectra and Mueller matrices for two scarab beetles. This is the first explicit instance of this data in the literature known to me. Michelson[1] (1911) describes the fact that the hand of the circular polarization reverses from the blue end of the spectrum to the red, and Gaubert[2] (1924)agrees with this. In a much later paper (1969), Neville and Caveney[5] disagree with this. The current results validate the results of Michelson and Gaubert with regard to this hand reversal, and in fact, it appears that there are two reversals in the visible wavelength region.

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